Int J Life Cycle Assess (2014) 19:1200–1213
DOI 10.1007/s11367-014-0730-5

LAND USE IN LCA

A framework for modelling the transport and deposition of eroded particles towards water systems in a life cycle inventory

Paula Quinteiro · Ana Cláudia Dias · Bradley G. Ridoutt · Luís Arroja

Received: 30 April 2013 / Accepted: 28 February 2014 / Published online: 18 March 2014
© Springer-Verlag Berlin Heidelberg 2014

Abstract
Purpose Topsoil erosion due to land use has been characterised as one of the most damaging problems from the perspective of soil-resource depletion, changes in soil fertility and net soil productivity and damage to aquatic ecosystems. On-site environmental damage to topsoil by water erosion has begun to be considered in Life Cycle Assessment (LCA) within the context of ecosystem services. However, a framework for modelling soil erosion by water, addressing off-site deposition in surface water systems, to support life cycle inventory (LCI) modelling is still lacking. The objectives of this paper are to conduct an overview of existing methods addressing topsoil erosion issues in LCA and to develop a framework to support LCI modelling of topsoil erosion, transport and deposition in surface water systems, to establish a procedure for assessing the environmental damage from topsoil erosion on water ecosystems.
Methods The main features of existing methods addressing topsoil erosion issues in LCA are analysed, particularly with respect to LCI and Life Cycle Impact Assessment methodologies. An overview of nine topsoil erosion models is performed to estimate topsoil erosion by water, soil particle transport through the landscape and its in-stream deposition. The type of erosion evaluated by each of the models, as well as their applicable spatial scale, level of input data requirements and operational complexity issues are considered. The WATEM-SEDEM model is proposed as the most adequate to perform LCI erosion analysis.
Results and discussion The definition of land use type, the area of assessment, spatial location and system boundaries are the main elements discussed. Depending on the defined system boundaries and the inherent routing network of the detached soil particles to the water systems, the solving of the multifunctionality of the system assumes particular relevance. Simplifications related to the spatial variability of the input data parameters are recommended. Finally, a sensitivity analysis is recommended to evaluate the effects of the transport capacity coefficient in the LCI results.
Conclusions The published LCA methods focus only on the changes of soil properties due to topsoil erosion by water. This study provides a simplified framework to perform an LCI of topsoil erosion by considering off-site deposition of eroded particles in surface water systems. The widespread use of the proposed framework would require the development of LCI erosion databases. The issues of topsoil erosion impact on aquatic biodiversity, including the development of characterisation factors, are now the subject of on-going research.

Keywords Life cycle inventory · Surface water systems · Topsoil erosion

Responsible editor: Jörg Schweinle

P. Quinteiro (✉) · A. C. Dias · L. Arroja
Centre for Environmental and Marine Studies (CESAM), Department of Environment and Planning, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal
e-mail: p.sofia@ua.pt

B. G. Ridoutt
Commonwealth Scientific and Industrial Research Organisation (CSIRO), Sustainable Agriculture National Research Flagship, Private Bag 10, Clayton South, Victoria 3169, Australia

1 Introduction

Topsoil provides ecosystem services essential for life. It acts as a water depuration filter and as a substrate for growing food, fibre and biomass; it provides habitats for multiple organisms, contributing to biodiversity, and it provides a foundation for construction activities. Topsoil erosion is a natural and complex process that varies around the world depending on climate, land use, soil texture, ground slope,

vegetation cover, rainfall patterns, and field-level conservation practices (Montgomery 2007). Awareness of the on-site impacts of accelerated topsoil erosion began as early as the 1920s (e.g., Bennett and Chapline 1928), and since then, topsoil erosion has become a worldwide major environmental issue. This process occurs in three stages: detachment and entrainment of soil particles, their transport and eventual deposition. Topsoil erosion has impacts that are both on-site (the place where the topsoil is detached) and off-site (wherever the eroded soil particles reach the surface water systems). The eroded soil particles may come from several sources: soil erosion (by water, wind and tillage), mining and construction activities (Grimm et al. 2002).

Because of the very slow rate of soil formation, any soil loss of more than 1 t ha^{-1} $year^{-1}$ can be considered as irreversible within a time span of 50–100 years. On average, the soil erosion rate for cropland is of the order of 7.5 t ha^{-1} $year^{-1}$ (Grimm et al. 2002; Wilkinson 2005). Water is one of the major causes of soil erosion (Jones et al. 2012a), and the average soil erosion by water in Europe is about 2.8 t ha^{-1} $year^{-1}$ (Jones et al. 2012a, b) affecting 60 % of the total land area excluding Russia. However, losses as high as 20–40 t ha^{-1} $year^{-1}$ have been measured in individual storms in Europe (Jones et al. 2012a).

In the last decades, the environmental damage to topsoil by water erosion has begun to be considered in Life Cycle Assessment (LCA) within the context of ecosystem services (EC JRC 2010; Guinée et al. 2006). Special attention has been given to changes in soil properties at the local level, which may include loss of soil nutrients, salinisation, changes in soil organic matter, reduction of soil depth, increase of stoniness and reduction of water-holding capacity.

However, there are also off-site impacts that affect aquatic biota caused by the eroded soil particles that are transported and deposited into surface water systems and into downstream soil. To date, these off-site impacts have not been considered in LCA, which is a substantial failing considering the scale of the problem.

The existence of life cycle inventory (LCI) data on soil erosion by water is crucial for the consideration of the associated impacts in LCA. Currently, there is no regionalised and/or local database of topsoil erosion by water. In addition, the spatial variability of soil texture and topographic parameters at a regionalised/local scale hampers the establishment of a conventional LCI. Therefore, to perform an unambiguous LCI of topsoil erosion, considering these spatial variabilities, it is necessary to use models based on geographic information systems (GIS).

Several different models for predicting the topsoil erosion by water and the transport of the detached soil particles into the surface water systems, for different scales of catchment areas, have been developed (Kirkby et al. 2004; Merrit et al. 2003; Van Rompaey et al. 2001a). However, these models have not been developed specifically for LCI purposes; they are applied primarily to watershed and river basin management issues, as well as to evaluate changes in water quality resulting from flood events and to assess siltation issues in catchment areas and navigable channels.

In this study, in order to understand how topsoil erosion issues have been considered in LCA, an overview of existing methods addressing topsoil erosion is conducted. Furthermore, to support LCI modelling and to fill the existing gap in current soil erosion research within the context of LCA, a framework for modelling soil erosion by water and deposition in water surface systems is proposed. Firstly, an overview of the range of different models available for estimating the quantity of soil particles detached and entrained by water, their transport through the landscape and ultimate deposition into the surface water systems is performed. Subsequently, the topsoil erosion model that best fits the inventory of an LCA study is suggested. The constraints of the suggested model are underlined, and with the goal of operationalising the LCI modelling, some proper simplifications are recommended.

2 Overview of LCA methods addressing topsoil erosion

Because of the scale of soil erosion, the integration of topsoil erosion issues in the LCA structure assumes significant relevance, contributing to the establishment of environmental strategies for soil protection (e.g., CEC 2006).

Figure 1 illustrates the general cause-effect chain of topsoil erosion and shows the damage to human health and terrestrial and aquatic ecosystems. The topsoil erosion process causes local changes to soil properties and leads to off-site deposition of eroded soil particles in surface water systems and downstream soil. This last pathway can bring off-site benefits for the downstream soil. When nutrients from the topsoil are transported from one place to another, the nutrients are redistributed downstream, which can lead to the increase of fertilisation of a downstream nutrient-deficient soil.

Table 1 presents the methods developed for assessing the impact of topsoil erosion within the LCA context. All the methods developed by Cowell and Clift (2000), Mattsson et al. (2000), Muys and García Quijano (2002), Garrigues et al. (2012) and Núnez et al. (2010) focus on topsoil erosion by water. However, Muys and García Quijano (2002) acknowledge that when relevant, both wind and tillage erosion should be considered. For wind erosion, the authors suggest using wind erosion equations following the methodology of Schwab et al. (1993), whereas for tillage erosion, no recommendations are forthcoming. With regard to the level of damage, all methods analyse the local effects of topsoil erosion, i.e., the changes to the soil properties pathway (Fig. 1), focusing mainly on soil quality and soil depth indicators.

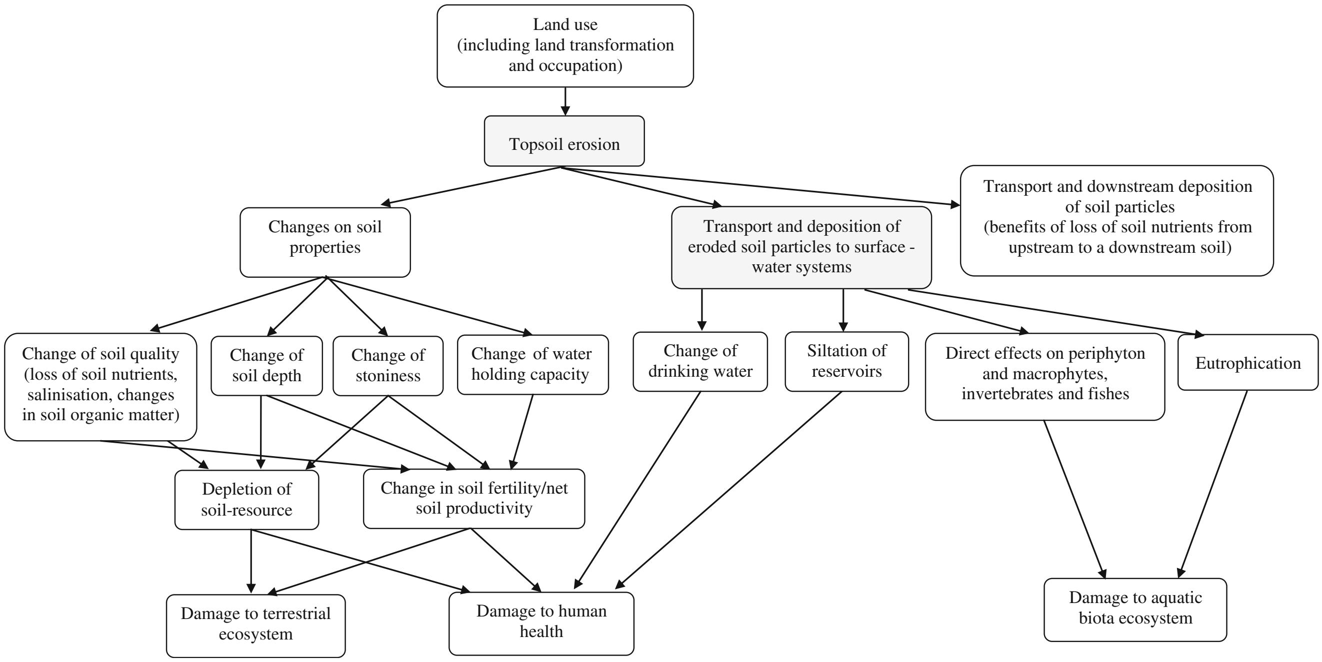

Fig. 1 Cause-effect chain of topsoil erosion impacts. The *shaded boxes* relate to the pathway focused on in this study

Núnez et al. (2013) applied the model following an endpoint approach, whereas the models proposed by the other authors evaluate the effects of topsoil erosion at the midpoint level. At the midpoint level, these methods proposed different impact categories such as depletion of the soil resource, soil fertility and desertification depending on the method, whereas at the endpoint level, the area of protection from damage to the terrestrial ecosystem is assessed. Several of these methods are not dedicated exclusively to topsoil erosion damage. In Muys and García Quijano (2002) and Garrigues et al. (2012), the indicator of the loss of soil is a sub-indicator in the soil sub-impact category; however, in Mattsson et al. (2000), the loss of soil is a sub-indicator in the soil fertility sub-impact category. These methods evaluate the topsoil erosion issues as a sub-category of the broader impact category of land use. In addition, at the endpoint level, Núnez et al. (2010) consider soil erosion as one of the four indicators (aridity, aquifer overexploitation, fire risk and erosion) for the desertification impact category.

At the LCI phase, in the Cowell and Clift (2000), Muys and García Quijano (2002) and Núnez et al. (2010) methods, the amount of topsoil eroded by water has been estimated by the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978). Garrigues et al. (2012) use the Revised Universal Soil Loss Erosion (RUSLE) equation (Renard et al. 1997). Both equations quantify the locally eroded soil particles but do not consider the runoff of these particles. However, the RUSLE equation presents some improvements in relation to the USLE, such as new calculation procedures to account for slope length and steepness, additional sub-factors for evaluating the cover and management factors for cropland and rangeland and new conservation practice values for cropland and rangeland (Jones et al. 1996). Further details about the RUSLE equation are given in Section 4.

With regard to the characterisation model, Cowell and Clift (2000) considered the Soil Static Reserve Life that is a function of the global reserves of agricultural soil (total topsoil in the world, in t) and current annual global net loss of topsoil mass by erosion (in t year^{-1}). Muys and García Quijano (2002) recommend transforming the loss of soil mass into a loss of soil depth (in m) using the bulk density of the soil. Therefore, the loss of soil depth over a period of 100 years is compared with the total rootable soil depth up to 1 m. However, neither method provides a set of operational characterisation factors (CFs). In fact, to derive such site-specific CFs, data on the reserve of the topsoil (area and depth of soil) under analysis is required. Both Mattsson et al. (2000) and Garrigues et al. (2012) use the loss of topsoil as an indicator for erosion impact. These authors argue that the estimates of loss of topsoil in the inventory level are informative enough to serve as impact indicators without requiring CFs. The characterisation model suggested by Núnez et al. (2010) takes into account the spatial area subjected to desertification, the decimal logarithm of the ecoregion area where desertification occurs and the time of perturbation. Moreover, this method proposes CFs for eight large natural areas, i.e., ecoregions (marine, prairie, temperate steppe, temperate desert, savanna, Mediterranean, tropical/subtropical steppe and tropical/subtropical desert) that consider the loss of topsoil and terrain definition/mass movement in each ecoregion soil weighted by the surface area of the ecoregion. Núnez et al. (2013) proposed an alternative characterisation model that considers the ultimate

Table 1 Overview of methods for inclusion of topsoil erosion issues in the LCA structure

Method	Cowell and Clift (2000)	Mattsson et al. (2000)	Muys and Garcia Quijano (2002)	Garrigues et al. (2012)	Núnez et al. (2010)	Núnez et al. (2013)
Cause of soil erosion	Water	Water	Water	Water	Water	Water
Level of damage	Local	Local	Local	Local	Local	Local
Impact pathway	Changes on soil properties—change of soil quality	Changes on soil properties—change of soil quality	Changes on soil properties—change of soil depth	Changes on soil properties	Changes on soil properties	Changes on soil properties—change of soil quality
Assessment level	Midpoint	Midpoint	Midpoint	Midpoint	Midpoint	Endpoint
Impact category	Depletion of soil resource	Soil fertility	Soil	Soil	Desertification	Damage to terrestrial ecosystem due to depletion of soil resource
Intervention	Loss of soil (t ha^{-1} $year^{-1}$)	Loss of soil (t ha^{-1} $year^{-1}$)	Loss of soil (t ha^{-1} $year^{-1}$)	Loss of soil (t ha^{-1} $year^{-1}$)	Loss of soil (t ha^{-1} $year^{-1}$)	Loss of soil (t ha^{-1} $year^{-1}$)
Erosion model	USLE	Not provided	USLE	RUSLE	USLE	USLE
Category indicator	Soil Static Reserve Life (SSRL)—total global soil reserve (m) in relation to current annual global net loss of topsoil (t $year^{-1}$)	Loss of soil	Loss of soil	Loss of soil	Loss of soil	Loss of soil
Characterisation model	SSRL	Unweighted aggregation	Soil depth loss over 100 years compared with total rootable soil depth	Unweighted aggregation	Desertification taking into account the spatial area subjected to desertification, the decimal logarithm of the ecoregion area where desertification occurs and the time of perturbation	Loss of soil as the local available soil reserves normalised with reference soil depth with transformation to emergy per unit of area and time of land use
Characterisation factor (CF)	Not provided	1 for all interventions (dimensionless)	Not provided	1 for all interventions (dimensionless)	1 or 2 for interventions depending on the ecoregion under analysis (dimensionless)	Spatial CF at resolution 10×10 km^2 $\left(MJ_{se} \times g_{soil\,loss}^{-1}\right)$

damage to the depletion of the soil resource by assessing the loss of soil as the locally available soil reserves normalised with a reference soil depth of 3 m with transformation to emergy units (megajoule solar equivalents) per unit of area and time of land use. A set of regional CFs was developed at a spatial resolution of 10×10 km^2, taking into account the locally available soil reserves, the reference soil depth and the solar energy factor (the quantity of solar energy that is required to generate a gram of eroded soil particles) (Núnez et al. 2013).

To our knowledge, there are no available LCI/Life Cycle Impact Assessment (LCIA) methods to assess the off-site effects due to topsoil erosion by water, i.e., the transport and deposition of eroded soil particles into surface water systems and the transport of soil particles from one place to another downstream (Fig. 1). Therefore, this study focuses on how to estimate topsoil erosion and to understand the transport of soil particles at the inventory level, evaluating the net quantity of soil particles that reaches the surface water systems.

3 Models of topsoil erosion

There are several purposes behind performing LCI modelling of topsoil erosion:

- To describe as accurately as possible the topographic conditions of the land use system under analysis and the types of erosion that can occur (sheet, rill and gully erosion)
- To characterise the soil profile, identifying the fraction of organic matter and the range size of the detached soil particles that reach the surface water systems
- To understand the influence of tillage operations on the quantity of eroded soil
- To quantify the quantity of detached soil particles that are transported and deposited into the surface water systems at sub-watershed level

The topsoil erosion models that have become used most widely for predicting eroded soil particles and their transportation and deposition into surface water systems are:

- ANSWERS—Areal Nonpoint Source Watershed Environment Response Simulations (Beasley et al. 1980; Dillaha et al. 2001)
- CREAMS—Chemical Runoff and Erosion from Agricultural Management System (Knisel 1980)
- GUEST—Griffith University Erosion System Template (Yu et al. 1997; Rose et al. 1997)
- HSPF—Hydrological Simulation Program Fortran (Johanson et al. 1980)
- TOPOG (Gutteridge and Davey 1991)
- WEPP—Watershed Erosion Prediction Project (Laflen et al. 1991)
- MIKE-11 (Hanley et al. 1998)
- WATEM-SEDEM—Water and Tillage Erosion Model-Soil particle Delivery model (Van Oost et al. 2000; Van Rompaey et al. 2001a)
- EUROSEM—European Soil Erosion Model (Borselli and Torri 2010; Morgan et al. 1998)

The goals, characteristics and limitations of each model are identified in Table 2. These models differ significantly regarding the type of erosion, their temporal and spatial scales, level of input data requirements, ease of use and in the algorithms used to predict the amount of detached and transported soil particles.

The spatially distributed ANSWERS model was developed to evaluate the effect of agricultural land use practices on water quality of sub-watersheds. This model predicts the topsoil erosion by adopting the physics-based continuity equations used by Foster and Meyer (1972). The transport of soil particles and nutrients is estimated using a form of Yalin's (1963) equation for bed load transport. The application of this model is limited by the large input data requirements, and it only considers sheet and rill erosion, disregarding gully erosion, which can be as extensive as the former two. Sheet erosion occurs by the detachment and entrainment of soil particles, which are then transported downslope by overland runoff (Hairsine and Rose 1992), whereas rill erosion occurs when the field slope increases, such that the overland runoff gains velocity, forming superficial channels (Rose 1993).

The CREAMS model estimates the topsoil erosion and deposition of soil particles applying the USLE (Wischmeier and Smith 1978). The transport of soil particles is simulated in the overland flow using a steady-state continuity equation (Foster's equation) at a plot sub-watershed level (range of 40–400 ha). The unlikely assumption that all areas of the study are uniform in soil topography is a pertinent source of uncertainty and inaccuracy in the predicted topsoil erosion.

The GUEST model predicts erosion, transport and deposition using physics-based equations describing the steady-state soil particle flux (Rose 1993). The model was developed to be applicable at plot sub-watershed level (<100 ha). Despite being an adequate spatial scale to perform an LCI around agricultural or forestry land use, this model assumes uniform soil topography and does not consider tillage operations.

In addition to topsoil erosion, both the HSPF and MIKE-11 models allow the assessment of in-stream water quality parameters (e.g., nitrogen, phosphorus, inorganic pollutants) at the watershed level. The HSPF model is applicable at the watershed level, in which the spatial area is divided into subregions with homogeneous hydrologic characteristics, i.e., homogenous edaphoclimatic data. The MIKE-11 model is also applicable at the watershed level, and the water system flow is described using physics-based St Venant equations.

Table 2 Goal, characteristics and limitations of models to predict topsoil erosion and the transport of soil particles to surface-water systems

Models	Goal and characteristics	Limitations
ANSWERS	• Developed to evaluate the effects of agricultural land use practices in the on-stream water quality • Applicable at sub-watershed level (>400 ha) • A long-term oriented model using a continuous time step (e.g., days) • Considers sheet and rill erosion	• Disregards gully erosion • Complex model requiring large input data (e.g., river network, total porosity of soil, infiltration control zone depth, erodibility, steady state infiltration, among others) • Does not take into account tillage operations • Requires calibration and validation
CREAMS	• Evaluates the effects of agricultural practices on pollutants in surface rainfall-runoff and topsoil erosion • Applicable at plot sub-watershed level (range of 40–400 ha) • Operates either on an event basis or long-term using a continuous time step (e.g., days) • Includes sheet, rill and ephemeral gully erosion • In addition to the prediction of topsoil erosion, also predicts the evapotranspiration of the crop, soil infiltration, among others	• Predicts topsoil erosion following the one-dimensional USLE approach • Assumes uniform topography (slope) of soil and land use • Does not take into account tillage operations • Complex model with large input data requirements (e.g., precipitation series, monthly air temperature and solar radiation values, crop type data, among others)
GUEST	• Developed to understand temporal fluctuations in soil particle concentration at the transport limit • Applicable at plot sub-watershed level (≤100 ha) • An event-oriented model • Considers sheet and rill erosion	• Assumes uniform topography (slope) of soil • Very complex model requiring large input data (e.g., runoff rate, length, width and slope of the soil, percent of sand grains of primary particles, soil particle/water-stable aggregate size distribution, among others) • Does not take into account tillage operations • The general lack of input data means that considerable effort is required to use it to predict topsoil erosion without prior calibration against parameterisation of field measurements
HSPF	• Developed to simulate the hydrology of watersheds and its in-stream water quality • Applicable at watershed level (~1,000 ha) • Operates either on an event basis or long-term using a continuous time step (from 1 min to 1 day, as long as the time step divides equally into 1 day) • Includes sheet, rill and ephemeral gully erosion • Takes into account tillage operations	• As inputs requires of precipitation data, estimates of potential evapotranspiration, topography, solar radiation, humidity, among others • Relies greatly on calibration against parameterisation of field measurements
TOPOG	• Simulates the soil particle balance through the landscape until the reaching the surface water system • Simulates the transient hydrologic behaviour of watersheds and how this is affected by changing watershed vegetation and by the growth of the vegetation • Applicable at plot sub-watershed and watershed levels (range of 10–1,000 ha) • Temporal resolution can be applied at daily time steps or sub-daily time steps • Uses detailed topographic information that can be provided by a digital elevation model of the area of study • Considers sheet and rill erosion	• Disregards gully erosion • Does not take into account tillage operations • Requires calibration
WEPP	• Developed to estimate net soil loss, the effect of hydraulic structures and impoundments on runoff flow and soil particle transport. • There are two versions: one that is applicable at plot sub-watershed (≤ 100 ha) and a second applicable at watershed level (~1,000 ha) • Operates either on an event basis or long-term using a continuous daily step • Includes sheet, rill and ephemeral gully erosion • Takes into account tillage operations	• Large computational and input data requirements (e.g., leaf area index, canopy cover and height, duration of runoff, bulk density of the soil, among others) • Relies on calibration against parameterisation of the field measurements
MIKE-11	• Used to predict topsoil erosion and to model the in-stream water quality • Applicable at watershed level • Operates either on an event or long-term basis • Uses detailed topographic information that can be provided by a digital elevation model of the area of study • Considers sheet and rill erosion	• Large input data requirements (e.g., hydrometric and topographic data, moisture content in surface and root zone, among others) • Does not take into account tillage operations • Low-quality data of the input parameters • Relies greatly on calibration against parameterisation of the field measurements

Table 2 (continued)

Models	Goal and characteristics	Limitations
WATEM-SEDEM	• Used to simulate eroded soil particles by the RUSLE method considering a two-dimensional landscape structure and the transport and deposition of soil particles into surface water systems • Applicable at plot sub-watershed and watershed levels • A long-term average annual deposition of soil particles in the surface-water systems • Focuses on the spatial resolution of 20×20 m • Includes sheet, rill and ephemeral gully erosion • Uses detailed topographic information that can be provided by a digital elevation model of the area of study • Takes into account tillage operations • Requires a modest amount of input data parameters • The parameter-based nature of the model allows an easy analysis of the contribution of individual parameters (sensitivity analysis) to the predicted topsoil erosion and deposition	• Low quality data of the input parameters • Requires partial calibration on the soil particle transport capacity
EUROSEM	• Predicts topsoil erosion • Applicable at plot sub-watershed level (≤100 ha) • Operates on an event basis considering a temporal resolution of minute-by-minute	• Only considers sheet and rill erosion • Large input data requirements (rainfall data, soil mechanical properties, topographical information, micro-topographical information, soil properties and vegetation information) • Does not take into account tillage operations • Low-quality data of the input parameters • Requires calibration and validation

Both models require large amounts of input data and overlook the relevance of gully erosion in a similar way to the ANSWERS and GUEST models. Gully erosion describes deep channels of runoff water and soil particles.

The TOPOG model describes water movement through the landscape, over the land surface, into the soil, through the soil and groundwater and back to the atmosphere via evaporation. Topsoil erosion is simulated, and the transport of soil particles is simulated following the Engelhund and Hansen (1968) equation. It disregards gully erosion processes, and it requires large and detailed input data.

The WEPP model evaluates net soil loss as well as the effects of hydraulic structures and impoundments on runoff flow and soil particle transport. It assesses the effects of tillage operations on the quantity of soil particles deposited into the surface water systems. The erosion and transport components are determined using the same relationships as the ANSWERS model. It tends to overpredict the transport of soil particles for small events and underpredict their transport for large events (Yu 2005). Gully erosion is disregarded at plot sub-watershed level, which does not happen at the watershed level.

The WATEM-SEDEM model predicts the long-term mean annual topsoil erosion following the RUSLE equation (Renard et al. 1997). It is applicable at plot sub-watershed and watershed levels, and it allows the evaluation of the influence of tillage operations on the quantity of eroded soil. Sheet, rill and ephemeral gully erosion processes are considered.

The EUROSEM model predicts topsoil erosion and simulates soil particle transport to the surface water systems at the plot sub-watershed level. However, it only simulates single intense rainfall-runoff events, i.e., long-term simulation of multiple rainfall-runoff events is a performance constraint. It overlooks the relevance of gully erosion in a similar way to the ANSWERS, GUEST, HSPF, MIKE-11 and TOPOG models.

4 Life cycle inventory modelling of topsoil erosion and deposition

4.1 Model suggestion and its overall structure

Because of the local or regional nature of topsoil erosion, the spatial differentiation assumes particular relevance. A model that performs an erosion-deposition inventory at a plot scale and uses site-dependent parameters allows the reduction of the uncertainty of the erosion LCI compared with generic default data on a broader scale. The ANSWERS, HSPF and MIKE-11 models have been developed to be applicable on a broad spatial scale. In addition, these models present operational complexity, require large amounts of input data, evaluate in-stream water quality, which is not an aim of the soil-deposition inventory, and require calibration. Although the ANSWERS model considers gully erosion and allows the inclusion of tillage operations, it is only applicable at the watershed level, i.e., the scale of assessment is approximately 1,000 ha, hindering the topsoil analysis of a local land use system. For these

reasons, these models are not adequate to perform an LCI of an agricultural or forestry system on a plot scale. The CREAMS and GUEST models also do not fit the erosion-deposition LCI purposes. Despite being applicable at a localised scale, these models consider uniform soil topography. Any model that uses a digital elevation model (DEM) to define the two-dimensional slope length parameter will reduce the underestimation of the erosion-deposition inventory of a non-uniform soil and land use. The shape of a slope affects the average topsoil eroded and the transport along the hill slope to the surface water system. For instance, according to Wischmeier and Smith (1978), the eroded soil from a convex slope can easily be 30 % greater than that from a uniform slope. In addition, these models disregard gully erosion and need calibration.

The EUROSEM model also does not fit the LCI purpose. It operates on an event basis, i.e., by each rainfall-runoff event. This means that to estimate the average eroded soil particles transported to the surface water systems during a sown-harvested crop land use study or forestry land use study, numerous simulations should be performed to obtain the cumulative erosion-deposition inventory. In addition, gully erosion is not considered, and it requires a large amount of input data, as mentioned in the previous section.

The WEPP model could be adequate for erosion-deposition inventory purposes as it is applicable at a plot sub-watershed level, operates on a long-term basis, considers gully erosion and takes into account the influence of tillage operations in the erosion and transportation of soil particles. However, the large computational and input data requirements and the calibration needed for many of the model parameters (e.g., slope, land cover, soil type) are shortcomings preventing its widespread use in LCI studies.

The WATEM-SEDEM model has the same characteristics as the WEPP model but requires fewer input data parameters. It is the only model that uses RUSLE (Renard et al. 1997) in considering the variability of soil texture and topographic parameters (elevation, slope, upslope, profile curvature). This acquires crucial relevance in establishing the routing network transport of soil particles to the water systems. Indeed, the primitive form of this equation, the USLE (Wischmeier and Smith 1978), and its update, the RUSLE, have been well-accepted by the LCA community for estimating the annual mass of topsoil loss, as mentioned in Section 2. However, both the primitive and RUSLE equations account only for the detached and entrained stages of the soil particles. The significant variability of soil texture and topographic parameters suggests the need for GIS to account for a less crude and unambiguous inventory of the detached soil particles deposited into the surface water systems. Indeed, performing a geospatial LCI is a step forward from conventional LCI studies. After considering the main characteristics and constraints of each model regarding performing an LCI of topsoil erosion, presented in Section 2, it is suggested that the use of the WATEM-SEDEM model is most appropriate.

The WATEM-SEDEM is a simple topography-driven model (Fig. 2) that uses the RUSLE equation (Eq. (1)) to estimate the topsoil eroded by water per land area (Renard et al. 1997):

$$A = R \times K \times \mathrm{LS}_{2\mathrm{D}} \times C \times P \tag{1}$$

where A is the average eroded soil per year (kg m^{-2} year^{-1}), R is the rainfall-runoff erosivity parameter (MJ mm m^{-2} h^{-1} year^{-1}), K is the soil erodibility parameter (kg h MJ^{-1} mm^{-1}) that represents the soil resistance to erosion by water and is related to the soil characteristics, namely, the

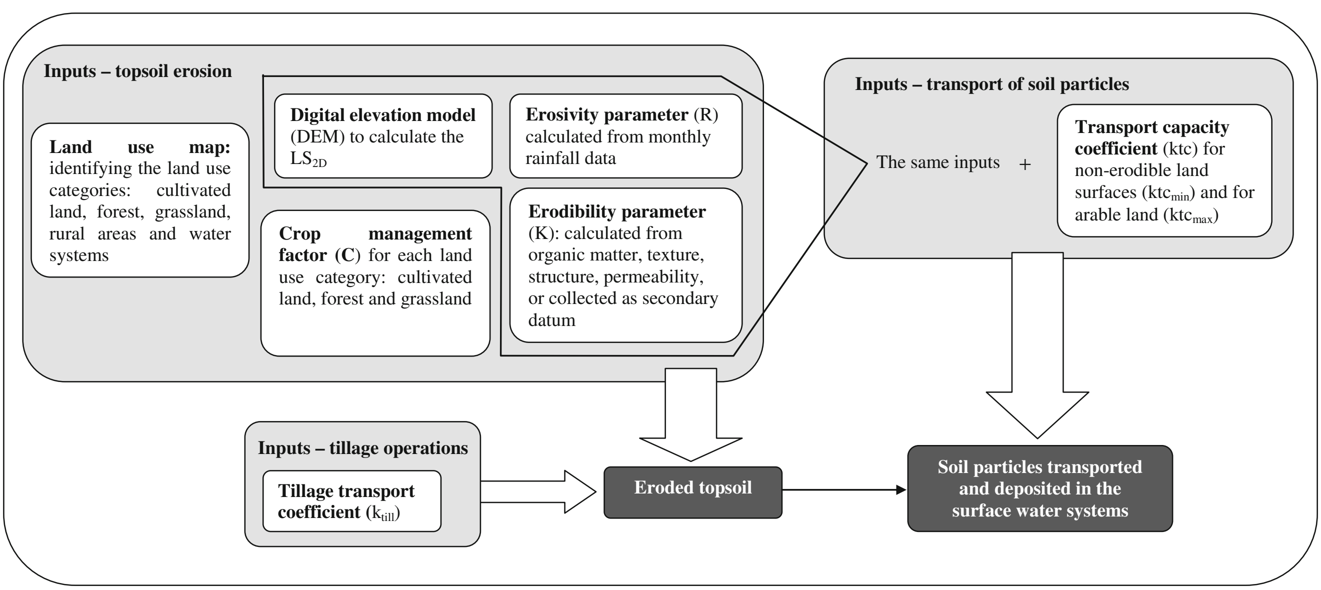

Fig. 2 An overview of the WATEM-SEDEM model structure distinguishing the topsoil eroded (kg m^{-2} year^{-1}), the transport of soil particles by overland runoff and their deposition in surface water systems (kg m^{-1} year^{-1})

structure, texture, organic matter content and permeability, LS_{2D} is the two-dimensional slope-length parameter (dimensionless), C is the cover-management parameter (dimensionless) allowing an understanding of the extent to which vegetation cover prevents soil erosion, and P is the support-practice parameter to reduce runoff and soil erosion (dimensionless).

The tillage erosion process is also simulated by the WATEM-SEDEM model following a diffusion-type equation (Eq. (2)) developed by Govers et al. (1994):

$$Q_{s,t} = -k_{till}\frac{dh}{dx} \tag{2}$$

where $Q_{s,t}$ is the rate of net downslope soil transport per tillage translocation (kg m^{-1} per tillage operation), k_{till} is the tillage transport coefficient (kg m^{-1} per tillage operation), h is the height at a given point of the hill slope (m), and x is the distance in the horizontal direction (m).

Unlike water erosion, topsoil displacement will only occur within the field, i.e., it is not transported directly to the surface water systems. However, these detached soil particles can contribute to the increase in the quantity of soil particles that are transported by overland runoff flow. This means that soil tillage operations have a non-negligible influence on topsoil erosion (Govers et al. 1994), and thus, they should be included in an LCI study.

The transport of the detached soil by overland runoff to the surface water systems is calculated according to Eq. (3). It is assumed that the transport capacity is proportional to the potential gully erosion (Desmet and Govers 1995; Van Oost et al. 2000; Van Rompaey et al. 2001a):

$$\mathrm{Tc} = \mathrm{ktc} \times R \times K \times \left(\mathrm{LS}_{2D} - 4.12 \times \mathrm{Sg}^{0.8}\right) \tag{3}$$

where Tc is the transport capacity (kg m^{-1} $year^{-1}$), ktc is the transport capacity coefficient (m), R, K and LS_{2D} are the parameters from the RUSLE equation, and Sg is the local slope gradient (dimensionless).

4.2 Guidelines and simplifications

In this section, the guidelines, methodological simplifications and recommendations for the LCI modelling of topsoil erosion using the WATEM-SEDEM model are identified and described.

4.2.1 Geographical area and multifunctionality

To estimate the quantity of detached soil particles from a land use system that reach the surface water systems, the geographical land area should be defined. Moreover, the LCI should include the classification of the land use type under analysis.

After the definition of the geographical land area, the next step is to delineate the related DEM, which represents the topographical variability of the soil. In addition to the GIS information, it is also necessary to establish a soil particle routing network, which represents the runoff flow through the landscape towards the surface water systems. For this, a land use map identifying the different land use types (for instance, cultivated land, forest, grassland, rural areas and water system) is required as an input to the WATEM-SEDEM model (Alatorre et al. 2010). The establishment of the soil particle routing network can raise the problem of incoherence between the pre-defined geographical land area under study and the overall downstream landscape, because the delineated DEM of the land use system under study may not match the land use map. To overcome this constraint, the DEM should be expanded to include all the downstream land area towards the surface water system. This highlights a system multifunctionality problem, because an overestimated erosion-deposition inventory is performed, i.e., it includes soil particles detached and transported from the land use system under study and downstream land use systems. As a result, in most cases, it is not possible to conduct an LCI study through a single run of the WATEM-SEDEM model. In order to assign the quantity of detached soil particles from the pre-defined land use system under study and its delivery to the surface water systems, a system subdivision should be carried out, as illustrated in Fig. 3. By considering the agricultural/forest land area under study and the downstream land area routing to the surface water system, two co-functions are provided by this unique system (AB) (the topsoil erosion process from the system under study and the topsoil

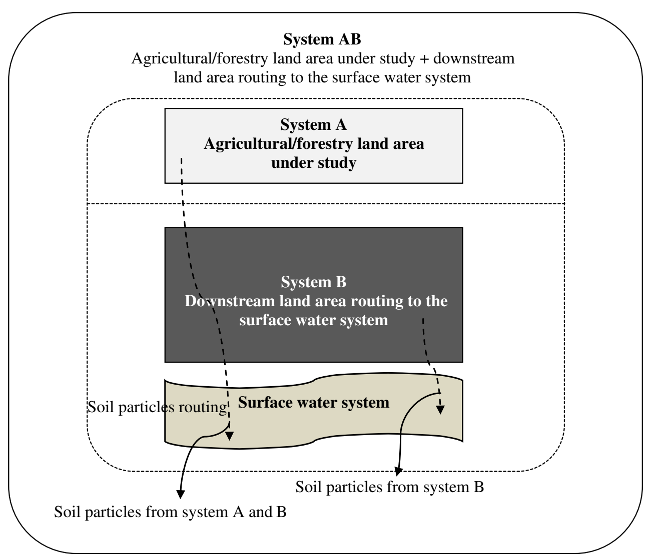

Fig. 3 Solving the system multifunctionality by subdivision of system AB. Subdivision aims to obtain the LCI topsoil erosion of system A

erosion process from the downstream landscape). Figure 3 shows that the inventory of the pre-defined land use system (system A) results from the subdivision of the overall system (AB). In practice, the LCI practitioner must have in mind that the spatially distributed WATEM-SEDEM model needs to be run at least twice to establish the inventory: the first run accounts for the inventory of the overall system (AB) and the second run accounts for the inventory of system B.

The exception occurs when the pre-defined land use system is located in the water system bank. In this case, it is reasonable to assume that all the eroded soil is transported to the water. In this case, the erosion-deposition inventory can be performed by the direct use of the RUSLE equation.

4.2.2 Input data requirements and simplifications

The input data requirements to perform an LCI modelling using the WATEM-SEDEM model are the soil erodibility parameter, rainfall-runoff erosivity parameter, two-dimensional topographical parameter, cover management parameter, tillage transport coefficient and the transport capacity coefficient of the soil particles.

Soil erodibility parameter (K) The soil erodibility parameter (K), as mentioned previously, describes the susceptibility to erosion by rainfall, and it depends on the texture, structure, organic matter, permeability and physico-chemical interactions of the soil. Generally, the availability of detailed primary soil data and soil erodibility parameters at the local scale is scarce. Therefore, instead of a soil erodibility map with a 20×20-m spatial resolution, the LCI practitioner can assume that the overall system (AB) has a single and a long-term average K parameter.

Depending on the soil profile, the average K parameter can be estimated following different approaches. If the silt fraction of soil does not exceed 70 %, the K value (kg h MJ^{-1} mm^{-1}) can be estimated using the nomograph developed by Wischmeier and Smith (1978) or by applying its algebraic approximation (Eq. (4)) (Renard et al. 1997):

$$K = \frac{2.1 \times 10^{-4}(12 - \mathrm{OM})M^{1.14} + 3.25(s-2) + 2.5(p-3)}{100 \times 7.59} \quad (4)$$

where OM is the fraction of organic matter (%), M is the particle-size parameter (percentage silt+fine sand fraction content)×(100-clay fraction), and s and p are the soil structure (dimensionless) and permeability classes (dimensionless), respectively.

If the soil profile has more than 70 % silt, the K parameter can be calculated following Eq. (5) (Wischmeier and Smith 1978):

$$K = 7.594\left\{0.0034 + 0.0405\exp\left[-0.5\left(\frac{\log D_g + 1.659}{0.7101}\right)^2\right]\right\} \quad (5)$$

where D_g is the geometric mean weight diameter of the primary soil particles (mm), which can be measured experimentally by analysing soil samples. This relationship is only validated for soil with less than 10 % of rock fragments by weight (fraction higher than 2 mm). When this equation is not valid, it is recommended to collect the input K parameter datum from literature (e.g., Borselli et al. 2009; Gómez et al. 2003; Irvem et al. 2007; Sanchis et al. 2008), national or international research projects (e.g., Van der Knijff et al. 2000) and soil databases attending to the texture of the soil under study. For instance, depending on the soil profile, this secondary datum can be collected from the Land Use and Cover Area frame Survey database (Panagos et al. 2012).

Rainfall-runoff erosivity parameter (R) The rainfall-runoff erosivity parameter (R) represents the impact of rain on topsoil erosion, and it is assessed based on monthly rainfall data that can be collected from meteorological stations within the land area under study and for a long-term period (for instance 20–30 years). When there are no meteorological stations within the land area, the average monthly precipitation data can be taken from the New_LocClim model (FAO 2005), which provides estimations of average climatic conditions at locations for which no observations are available, considering the nearest neighbour interpolation method. In these situations, the R parameter can be calculated using Eqs. (6), (7) and (8) (Renard and Freimund 1994):

$$\mathrm{MF} = \frac{\sum_{i=1}^{12} p_i^2}{P} \quad (6)$$

$$R = 0.7397 \times \mathrm{MF}^{1.847}, \quad \text{for } \mathrm{MF} < 55\mathrm{mm} \quad (7)$$

$$R = 95.77 - 6.081 \times \mathrm{MF} + 0.4770 \times \mathrm{MF}^2, \quad \text{for } \mathrm{MF} > 55\mathrm{mm} \quad (8)$$

where MF is the Modified Fournier index (mm) (Arnoldus 1977), p_i is the average monthly precipitation (mm), and P is the average annual precipitation (mm). Attending to the area of assessment, i.e., plot sub-watershed level, it is recommended to assume that the spatial variability of parameter R is negligible. Therefore, the long-term variability of R on a yearly basis is considered uniform for the entire study area.

Two-dimensional topographical parameter (LS_{2D}) The two-dimensional topographical parameter (LS_{2D}) shows the

impact of the length and slope of the landscape on soil erosion, and it has a large value whenever the length and slope of the landscape are large. In WATEM-SEDEM, the DEM is used to calculate the LS_{2D} parameter.

Cover management parameter (C) The cover management parameter (C) reflects the effect of cropping and management practices on erosion rates, i.e., it indicates the extent to which the vegetation cover prevents topsoil erosion. This parameter depends on the size of cover plants, the state of the surface area, plant roots, surface roughness and amount of contained water (Park et al. 2011). There is very limited availability of C parameters for different crops and/or forests at different locations (Núnez et al. 2013). Because of this lack of data, Núnez et al. (2013) developed a methodology to estimate specific C parameters for agricultural and/or forestry systems. However, this approach requires a follow-up field to calculate the percentage of vegetative cover throughout the sown-harvest process. To overcome this time-consuming procedure, we suggest using single values concerning the land use categories included in the defined overall system (AB), as well as in system B: crop, forestry and/or grassland. Even though this increases the uncertainty of the inventory results, it is the best way in which to minimise the complexity of calculating C parameters at the plot scale. If the system (AB) encompasses various types of crops and/or forestry land use, a weighted average between each culture cover management and the occupied area should be performed. The C parameters can be collected from scientific publications (e.g., Lee and Lee 2006; Keesstra et al. 2009; Yang et al. 2003), books and reports (e.g., Almorox et al. 1994; Pimenta 2003; Van der Knijff et al. 2000).

Transport capacity coefficient of soil particles (ktc) The transport capacity coefficient of soil particles (ktc) depends on the local land vegetative cover and represents the slope length needed to runoff an equivalent quantity of topsoil particles from a bare surface with a similar slope gradient (Verstraeten 2006). The WATEM-SEDEM model requires distinction between arable land surfaces, ktc_{max} (cultivated land), and non-erodible land surfaces, ktc_{min} (forests and/or grassland). Moreover, Van Rompaey et al. (2001a) have indicated that a calibration of transport capacity coefficient would be desirable because of the unique and specific routing network of soil particles for each land use system. In fact, land use systems with high rainfall erosivity also present high runoff flows and soil particle deposition into the surface water system resulting in higher transport capacity (Verstraeten et al. 2007). Because of the unavailability of sufficient data to calibrate ktc_{max} and ktc_{min} separately, Verstraeten (2006) suggested maintaining a fixed ratio of ktc_{max}/ktc_{min} values. For instance, the following typical values between ktc_{min} and ktc_{max} have been used: 1:3.33 in central Belgium and the southwestern part of Slovenia (Keesstra et al. 2009; Verstraeten et al. 2006; Verstraeten 2006) and in Spain (Alatorre et al. 2010); values ranging between 1:3.80 and 1:2.20 for mountainous and non-mountainous areas in Italy (Van Rompaey et al. 2005); 1:3.89 for seven small catchments in South Africa (Van Rompaey et al. 2001b; Verstraeten et al. 2001) and 1:2.50 for the Czech Republic (Van Rompaye et al. 2003). The LCI practitioner should compare the topographic characteristics (e.g., LS_{2D}) of the land use system under study with the characteristics of the several regions mentioned above. Regions with similar topographic characteristics should be characterised by similar ktc_{max}/ktc_{min} ratios.

Data on annual suspended soil particles input into the water system channels under study, as well as data on rainfall erosivity for the same time series, are required to perform the calibration. For each combination of ktc_{max} and ktc_{min}, a quantity of soil particles delivered into the surface water system is predicted, allowing the comparison of the quantities predicted by the model and those measured. The Nash-Sutcliffe model efficiency statistic (NS) (Nash and Sutcliffe 1970) is used as a measure of likelihood following Eq. (9):

$$\mathrm{NS} = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2} \tag{9}$$

where n is the number of observations, O_i is the measured soil particles in the water system, P_i is the predicted soil particles in the water system, and $\overline{O}$ is the average of the measured soil particles. NS can range from $-\infty$ to 1 and represents the proportion of the initial variance accounted for by the model. The closer the value of NS is to 1, the more efficient is the model (Alatorre et al. 2010).

Tillage transport coefficient (k_{till}) The intensity of topsoil erosion is influenced by the tillage transport coefficient (k_{till}). Experimental tillage erosion studies have shown that tillage erosivity is affected by parameters other than slope gradient, such as tillage depth, tillage speed and soil condition (Gerontidis et al. 2001). Van Muysen et al. (2000) presented a dataset of (k_{till}) calculated for different implements, tillage speed and tillage depth. In addition, (k_{till}) following the up- and down-slope tillage direction for each implementation can be calculated following Eq. (10) (Van Muysen et al. 2002):

$$k_{\mathrm{till}} = 2.026 \times \rho_{\mathrm{b}} \times D^{1.989} \times v^{0.406} \tag{10}$$

where ρ_{b} is the bulk density of the soil (kg m^{-3}), D is the tillage depth (m), and v is the tillage speed (m s^{-1}). For a set of tillage operations during the sown-harvest cycle, the tillage transport coefficient is the sum of the coefficients for each individual operation.

When the system (AB) encompasses cultures that require different tillage operations, a weighted average tillage transport coefficient should be used.

4.2.3 *Complexity of LCI modelling and uncertainty parameters*

When defining the scope of the study, special attention should be given to the definition of the geographic system boundary, identifying and reporting the location of the land use system. On the one hand, depending on the spatial location of the land use, different modelling procedures can be followed. In some situations, as described in Section 4.2.1, a system subdivision is required to solve the multifunctional and to predict the erosion-deposition inventory of the pre-defined land use system.

On the other hand, depending on the area of assessment, it can include different land use types and huge variability of soil properties. From an ideal perspective, a map that could show the variability of each input parameter necessary to estimate the quantity of topsoil eroded would be desirable.

However, currently, this is an unrealistic procedure because of the non-availability of the required input data. First, there are no specific or site-generic LCI databases containing soil erodibility and cover management maps. In particular, data related to cover management parameters for specific cultures and locations are quite rare. Secondly, although it is possible to perform experimental measurements during the overall growth of the crop/forestry from sowing to harvest, this is impracticable from a time and economic point of view. Therefore, to overcome these constraints and to operationalise the LCI inventory, it seems reasonable to use an average value for each input parameter, i.e., constant values instead of maps.

The overall uncertainty of the erosion-deposition LCI is caused by the empirical inaccuracy of the input data, unrepresentative data, lack of data sets and inherent uncertainties of the model. Perhaps the biggest problem with the modelling of eroded soil and its transport to the surface water systems, related to the availability and reliability of input data, is that the transport capacity coefficient is a major source of uncertainty and inaccuracy in an LCI performed with the WATEM-SEDEM model (Van Rompaey et al. 2001a; Verstraeten et al. 2006). To understand the influence of a set of different ktc_{max}/ktc_{min} ratios on the mass of soil particles detached and deposited, a sensitivity analysis is recommended. Moreover, the influence of other input parameters, for instance, K, C and k_{till} , which are considered constant and/or adapted from literature, should also be evaluated.

5 Conclusions

The existing LCA methods addressing soil erosion focus only on the local changes of soil properties. They differ in the way that they quantify erosion at the LCI level and in the LCIA methodology, namely, in the assessment level (midpoint/endpoint), impact pathway, category indicator, characterisation model and characterisation factors. None of these methods considers the transport and deposition of the eroded particles towards the surface water systems. This study provides the first step for the inclusion of this issue in the LCA structure. The conducted overview of erosion models shows that there is a range of available models for predicting the quantity of detached soil particles and their transport towards the surface water systems. Following consideration of their operational complexity, input requirements and spatial scales, it has been suggested that the WATEM-SEDEM model is most appropriate for performing an LCI analysis. Therefore, this paper provides a framework with which to perform an LCI of the topsoil eroded and transported towards the surface water systems. This operational framework has the following key points:

- Definition of the spatial land area of assessment (system boundary) stating its geographical location.
- When necessary, a system subdivision should be performed to avoid allocation procedures, depending on the pre-defined land use systems (allocation procedures).
- Collecting all the required input data to run the WATEM-SEDEM model.
- Performing a sensitivity analysis to evaluate the influence of the transport capacity coefficient on the LCI results.

This framework seems to be a reasonable approach to establish realistic estimations of the order of magnitude of topsoil erosion and the amount of soil particles that reach the surface water systems, causing turbidity and in-stream soil particle deposition, which in turn affect aquatic biota.

It should be noted that this framework should be operationalised by performing case studies. Moreover, displaced soil particles are themselves a source of potential environmental harm, especially when they reach water systems. Therefore, a method to evaluate the impact of topsoil erosion on aquatic biodiversity within the LCIA is also required, and it is the subject of on-going research.

Acknowledgments The authors gratefully acknowledge FCT (Science and Technology Foundation-Portugal) for scholarships granted to Paula Quinteiro (SFRH/BD/78690/2011) and Ana Cláudia Dias (SFRH/BPD/75788/2011).

References

Alatorre LC, Beguería S, García-Ruiz JM (2010) Regional scale modelling of hillslope soil particle delivery: a case study in the Barasona Reservoir watershed (Spain) using WATEM/SEDEM. J Hydrol 391: 109–123

Almorox J, De Antonio R, Saa A, Cruz Díaz M, Gasco JM (1994) Methods for estimating water erosion. Ed. Agrícola Española (in Spanish)

Arnoldus HMJ (1977) Methodology used to determine the maximum potential average annual soil loss due to sheet and rill erosion in Morocco. FAO Soil Bull 34:39–51

Beasley DB, Huggins LF, Monke EJ (1980) ANSWERS: a model for watershed planning. T ASAE 23:938–944

Bennett HH, Chapline WR (1928) Soil erosion: a national menace United States Department of Agriculture, Circular 033

Borselli L, Cassi P, Sanchis P (2009) Soil erodibility assessment for applications at watershed scale. In Constantini, EAC (ed) Manual of methods for soil and land evaluation, Science Publisher, Chapter 5, pp 98–117

Borselli L, Torri L (2010) EUROSEM 2010: European Soil Erosion Model. http://www.lorenzo-borselli.eu/eurosem/. Accessed December 2012

CEC (2006) Proposal for a directive of the European Parliament and of the Council establishing a framework for the protection of soil and amending Directive 2004/35/EC. European Council and the European Commission Brussels, 22.9.2006, COM(2006) 232 final, 2006/0086

Cowell SJ, Clift R (2000) A methodology for assessing soil quantity and quality in life cycle assessment. J Clean Prod 8(4):321–331

Desmet PJJ, Govers G (1995) GIS-based simulation of erosion and deposition patterns in an agricultural landscape: a comparison of model results with soil map information. Catena 25:389–401

Dillaha TA, Wolfe ML, Shirmohammadi A, Byne FW (2001) ANSWERS-2000. In: Parsons JE, Thomas DL, Huffman RL (eds) Non-point source water quality models: their use and application. Final report of USDA-CSREES southern region research project S-273, Development and Application of Comprehensive Agricultural Ecosystems Models

EC JRC (European Commission, Joint Research Centre). International Reference Life Cycle Data System (ILCD) (2010) Handbook - General guide for Life Cycle Assessment—detailed guidance. European Commission - Joint Research Centre - Institute for Environment and Sustainability, first ed. EUR 24708 EN. Publications Office of the European Union, Luxembourg

Engelhund F, Hansen E (1968) A monograph on soil particle transport in alluvial streams. Teknish Forlag, Technical Press, Copenhagen

FAO (2005) New LocClim, Local Climate Estimator CD-ROM, Food and Agriculture Organization. Rome, Italy. www.fao.org/nr/climpag/pub/en3_051002_en.asp. Acessed November 2012

Foster GR, Meyer LD (1972) Transport of soil particles by shallow flow. Trans ASAE 15(1):99–102

Garrigues E, Corson MS, Walter C, Angers DA, van der Werf H (2012) Soil-quality indicators in LCA: method presentation with a case study. 8th Int Conference on LCA in the Agri-food sector, 1–4 October, Saint-Maio, France

Gerontidis S, Kosmas C, Detsis B, Marathianou M, Zafirou T, Tsara M (2001) The effect of mouldboard plough on tillage erosion along a hillslope. J Soil Water Conserv 56:147–152

Gómez JA, Battany M, Renschler CS, Fereres E (2003) Evaluating the impact of soil management on soil loss in olive orchards. Soil Use Manag 19:127–134

Govers G, Vandaele K, Desmet P, Poesen J, Bunte K (1994) The role of tillage in soil redistribution on hillslopes. Eur J Soil Sci 45:469–478

Grimm M, Jones R, Montanarella L (2002) Soil erosion risk in Europe. European Soil Bureau. Institute for Environment and Sustainability. EUR 19939 EN

Guinée J, Van Oers L, de Koning A, Tamis W (2006) Life cycle approaches for conservation agriculture. CML report 171. Department of Industrial Ecology and Department of Environmental Biology, Leiden, the Netherlands

Gutteridge Haskins and Davey (1991) Integrated quantity/quality modelling—stage 3. Gutteridge Haskins & Davey for Department of Water Resources. Sydney

Hairsine P, Rose C (1992) Modelling water erosion due to overland flow using physical principles: 1. Sheet flow. Water Resour Res 28(1): 237–293

Hanley N, Faichney R, Munro A, Shortle JS (1998) Economic and environmental modelling for pollution control in an estuary. J Environ Manag 52:211–225

Irvem A, Topaloglu F, Uygur V (2007) Estimating spatial distribution of soil loss over Seyhan River Basin in Turkey. J Hydrol 336(1–2):30–37

Johanson RC, Imhoff JC, Davis HH (1980) User's manual for the Hydrologic Simulation Program–Fortran (HSPF), version 5.0, EPA-600/9-80-105. US EPA Environmental Research laboratory, Athens, Greece

Jones A, Panagos P, Barcelo S, Bouraoui F, Bosco C, Dewitte O, Gardi C, Erhard M, Hervás J, Hiederer R, Jeffery S, Lukewillw L, Marmo L, Montanarella L, Olazábal C, Petersen J-E, Penizek V, Strassburger T, Tóth G, Van Den Eechaut M, Van Liedekerke N, Verheijen F, Viestova E, Yigini Y (2012a) The state of soil in Europe. JRC reference reports, European Commission. Office for official publications of the European Communities, Luxemburg

Jones A, Bosco C, Yigini P, Montanrella L (2012b) Soil erosion by water: 2011 update of IRENE agri-environmental indicator 21. JRC Scientific Report JRC 68729

Jones DS, Kowalski DG, Shaw RB (1996) Calculating Revised Universal Soil Loss Equation (RUSLE) estimates on Department of Defense Lands: a review of RUSLE factors and U.S. Army Land Condition-Trend Analysis (LCTA) data gaps. CEMML Publications, TPS 96:8

Keesstra SD, van Dam O, Verstraeten G, van Huissteden J (2009) Changing soil particle dynamics due to natural reforestation in the Dragonja catchment, SW Slovenia. Catena 78(1):60–71

Kirkby MJ, Jones RJA, Irvine B, Gobin A, Govers G, Cerdan O, Van Rompaey AJJ, Le Bissonnais Y, Daroussin J, King D, Montanarella L, Grimm M, Vieillefont V, Puigdefabregas J, Boer M, Losmas C, Yassoglou N, Tsara M, Mantel S, Van Lynden G (2004) Pan-European Soil Erosion Risk Assessment: the PESERA map, version 1 October 2003. Explanation of special publication nº 73. European Soil Bureau research report nº16. Office for official publication of the European Communities, Luxemburg

Knisel WG (1980) CREAMS: a field scale model for chemicals, runoff and erosion from agricultural management systems. United Stated Department of Agriculture

Laflen LJ, Renard KG, Foster GR (1991) WEPP: a new generation of erosion prediction technology. J Soil Water Conserv 46:34–38

Lee GS, Lee HS (2006) Scaling effect for estimating soil loss in the RUSLE model using remotely sensed geospatial data in Korea. Hydro Earth Syst Sci Discuss 3:135–157

Mattsson B, Cederberg C, Blix L (2000) Agricultural land use in life cycle assessment (LCA): case studies of three vegetable oil crops. J Clean Prod 8:283–292

Merrit WS, Letcher RA, Jakeman AJ (2003) A review of erosion and soil particle transport models. Environ Model Softw 18:761–799

Montgomery DR (2007) Soil erosion and agricultural sustainability. PNAS 104:13268–13272

Morgan RPC, Quinton JN, Smith RE, Govers G, Poesen JWA, Auerswald K, Chisci G, Torri D, Styczen ME (1998) The European Soil Erosion Model (EUROSEM): a dynamic approach for predicting soil particle transport from fields and small catchments. Earth Surf Proc Land 23:527–544

Muys B, Garcia Quijano J (2002) A new method for Land Use Impact Assessment in LCA based on ecosystem exergy concept, Internal report. Laboratory for Forest, Nature and Landscape Research, Leuven

Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models—part 1: a discussion of principles. J Hydrol 10:282–290

Núnez M, Civit B, Munoz P, Arena AP, Rieradevall J, Antón A (2010) Assessing potential desertification environmental impact in life cycle assessment. Int J Life Cycle Assess 15:67–78

Núnez M, Antón A, Munoz P, Rieradevall J (2013) Inclusion of soil erosion impacts in life cycle assessment on a global scale: application to energy crops in Spain. Int J Life Cycle Assess 18:755–767

Panagos P, Meusburger K, Alewell C, Montanarella L (2012) Soil erodibility estimation using LUCAS point survey data of Europe. Environ Model Softw 30:143–145

Park S, Oh C, Jeon S, Jung H, Choi C (2011) Soil erosion risk in Korean watersheds, assessed using the revised universal soil loss equation. J Hydrol 399(3–4):263–273

Pimenta MT (2003) Guidelines for the application of equation universal soil loss in GIS: the culture factor C and soil erodibility factor K. INAG/DSRH. Sistema Nacional de Informação de Recursos Hídricos/Direcção de Seviços dos Recursos Hídricoa-DSRH (in Portuguese)

Renard KG, Freimund JR (1994) Using monthly precipitation data to estimate the R-factor in the revised USLE. J Hydrol 157:287–306

Renard KG, Foster GR, Weesies GA, Mc Cool DK, Yoder DC (1997) Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). Agricultural Handbook no. 703, United States Department of Agriculture

Rose CW (1993) Erosion and soil particleation. In: Bonell M, Hufschmidt MM, Gladwell JS (eds.) Hydrology and water management in the humid tropics: hydrological research issues and strategies for water management. Cambridge University Press, pp 301–343

Rose CW, Coughlan KJ, Ciesiolka LAA, Fentie B (1997) Program GUEST (Griffith University erosion system template), a new soil conservation methodology and application to cropping systems in tropical steeplands. ACIAR technical reports

Sanchis MPS, Torri D, Borselli L, Poesen J (2008) Climate effects on soil erodibility. Earth Surf Proc Land 33:1082–1097

Schwab GO, Fangmeier DD, Elliot WJ (1993) Soil and water management systems. Wiley, New York

Van der Knijff R, Jones R, Montanarella L (2000) Soil erosion risk, assessment in Europe. Join Research Centre. European Soil Bureau

Van Muysen W, Govers G, Van Oost K, Van Rompaey A (2000) The effect of tillage depth, tillage speed and soil condition on chisel tillage erosivity. J Soil Water Conserv 55:354–363

Van Muysen W, Govers G, Van Oost K (2002) Identification of important factors in the process of tillage erosion: the case of moulboard tillage. Soil Tillage Res 65:77–93

Van Oost K, Govers G, Desmet PJJ (2000) Evaluating the effects of changes in landscape structure on soil erosion by water and tillage. Landsc Ecol 15:577–589

Van Rompaey A, Verstraeten G, Van Oost K, Govers G, Poesen J (2001a) Modelling mean annual soil particle yield using a distributed approach. Earth Surf Proc Land 26:1221–1236

Van Rompaey A, Verstraeten G, Van Oost K, Rozanov A, Govers G, Poesen J (2001b) Modelling soil particle transport in the Jonkershoek catchment. Part 1: model calibration and validation. In: Cartographic Modelling of Land Degradation, Proceedings of the Workshop held in Ghent (September 2001) in the Framework of the Bilateral Cooperation between Flanders and South-Africa

Van Rompaye A, Krasa J, Dostal T, Govers G (2003) Modelling sediment supply to rivers and reservoirs in Eastern Europe during and after the collectivisation period. Hydrobiologia 494(1–3):169–176

Van Rompaey A, Bazzoffi P, Jones RJA, Montanarella L (2005) Modelling sediment yields in Italian catchments. Geomorphology 65:157–169

Verstraeten G (2006) Regional scale modelling of hillslope soil particle delivery with SRTM elevation data. Geomorphology 81:128–140

Verstraeten G, Poesen J, Gillijns K, Govers G (2006) The use of riparian vegetated filter strips to reduce river soil particle loads: an overestimated control measures? Hydrol Process 20:4259–4267

Verstraeten G, Prosser IP, Fogarty P (2007) Predicting the spatial patterns of hillslope soil particle delivery to river channels in the Murrumbidgee catchment, Australia. J Hydrol 334:440–454

Verstraeten G, Van Rompaey A, Van Oost K, Rozanov A, Poesen J, Govers G (2001) Modelling soil particle transport in the Jonkershoek catchment. Part 2: evaluating the impact of possible land use changes on soil particle delivery to the Eerste Rivier and the Jonkershoek reservoir. In: Cartographic Modelling of Land Degradation, Proceedings of the Workshop held in Ghent (September 2001) in the Framework of the Bilateral Cooperation between Flanders and South-Africa

Wilkinson BH (2005) Humans as geologic agents: a deep-time perspective. Geology 33:161–164

Wischmeier WH, Smith DD (1978) Predicting soil erosion losses: a guide to conservation planning. USDA Agricultural Handbook, nº537

Yalin MS (1963) An expression for bed load transportation. J Hydraul Division American Society of Civil Engineers 98 (HY3), 221–250

Yang D, Kanae S, Oki T, Koike T, Musiake K (2003) Global potential soil erosion with reference to land use and climate changes. Hydrol Process 17:2913–2928

Yu B (2005) Process-based erosion modelling: promises and progress. In: Bruijnzell LA, Bonell M (eds) Forests, water and people in the humid tropics: past, present and future, Hydrological research for integrated land and water management. Cambridge University Press, Cambridge. ISBN 0511109415

Yu B, Rose CW, Ciesiolka CAA, Coughlan KJ, Fentie B (1997) Towards a framework for runoff and soil loss prediction using GUEST technology. Aust J Soil Res 51191–1212